EIC ACCELERATOR COLLABORATION MEETING 2019

IR Magnets – Recent Advances

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Acknowledgements

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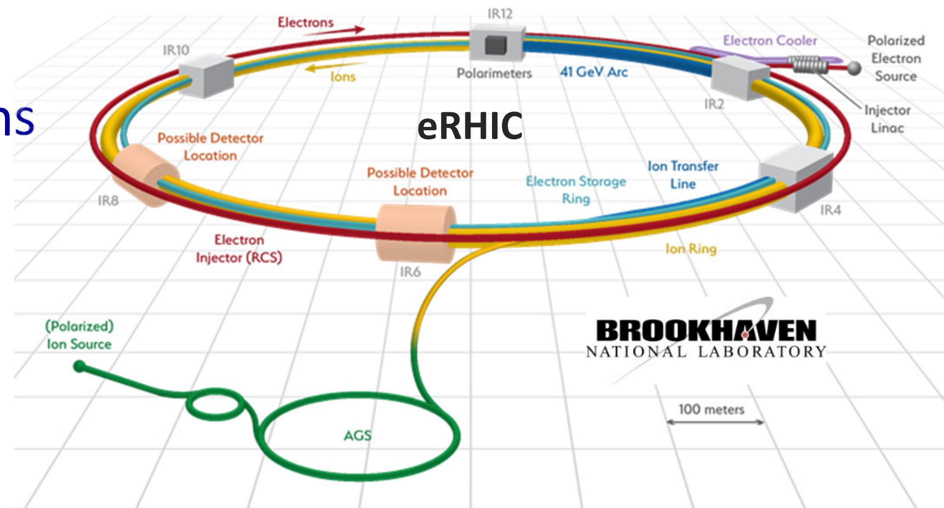
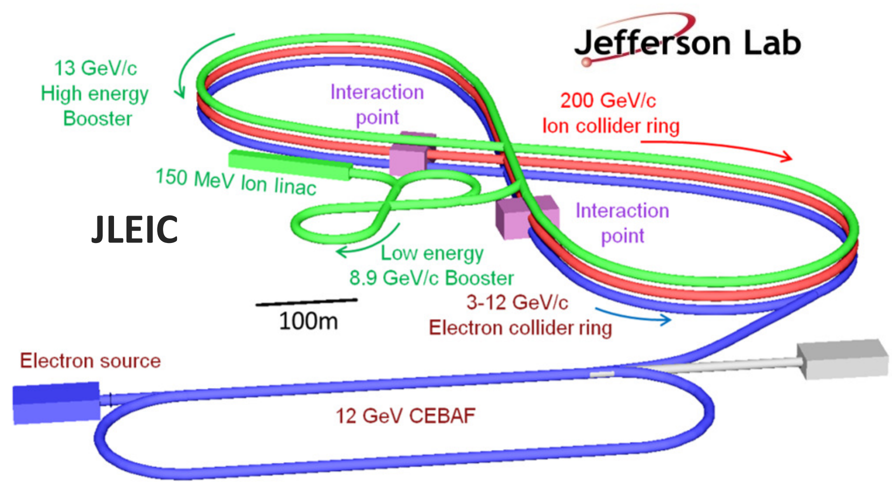
Presentation Outline

1. IR Magnet requirements
2. Conductor and Technology Options
3. Magnet parameters and features
   - *Downstream ion quadrupoles*
   - *Upstream ion quadrupoles*
   - *Electron Quadrupoles*
4. Magnetic design and field quality
   - *Magnet straight section*
   - *Coil ends*
5. High Gradient Quadrupole R&D
6. Summary





EIC IR Design Requirements

Experimental:

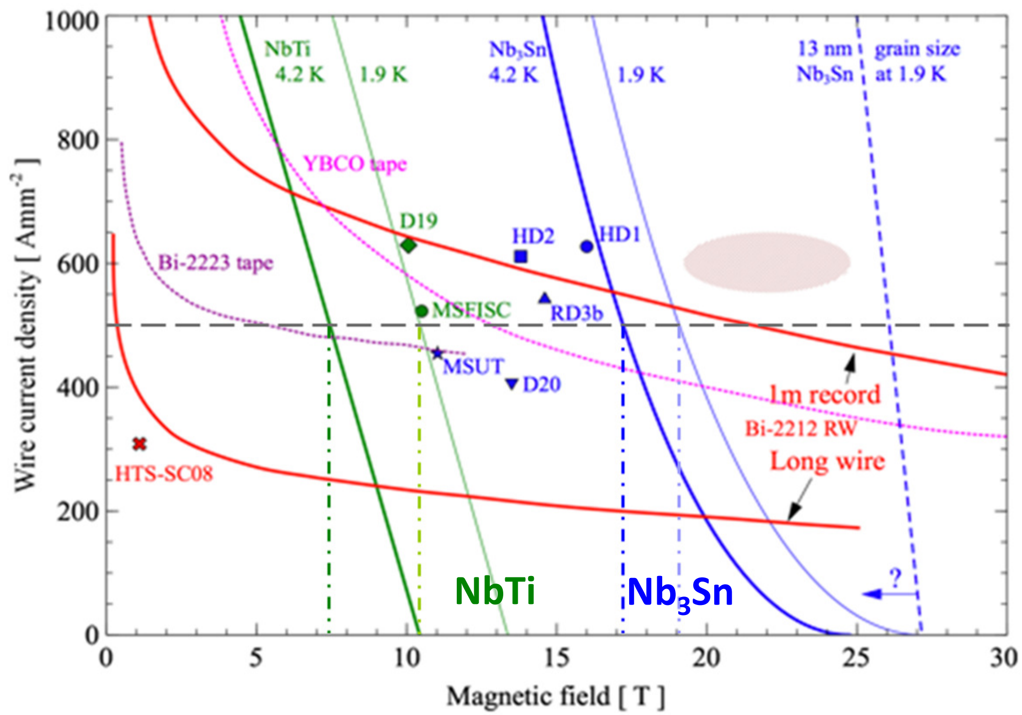
- **Acceptance of charged and neutral particles** in the forward direction of the hadron beam
- Operation in a **wide range of beam energy**
- Limit **background and detector damage from e-beam synchrotron radiation**

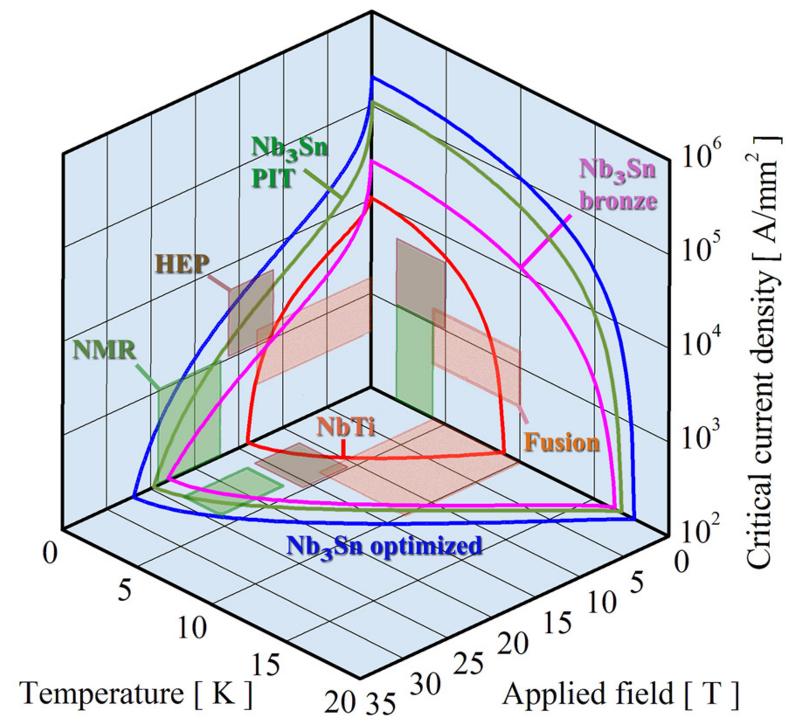
Accelerator and IR magnets:

- **Combined large aperture and gradient** in downstream ion quadrupoles for acceptance and small beam size at the IP
- **Good field quality** from low to high current
- **Compact designs** and/or **interleaved electron and ion magnets** in order to minimize **crossing angle** and **crab cavity system** requirements
- **Control magnet fringe fields** to minimize perturbations on adjacent beam
- **Individually optimized magnets** to address local constraints and maximize performance

Conductor Options

Material	Max. Field	Reaction	Max stress/strain	Insulation	Coil Parts
NbTi	10-11 T	N/A	Limited by coil composite	Polyimide	G-10
Nb_3Sn	17-19 T	~650 C	$\sigma_\theta < 200$ MPa, $\varepsilon_z < 0.2\%$	Fiberglass/epoxy	Ti, Stainless

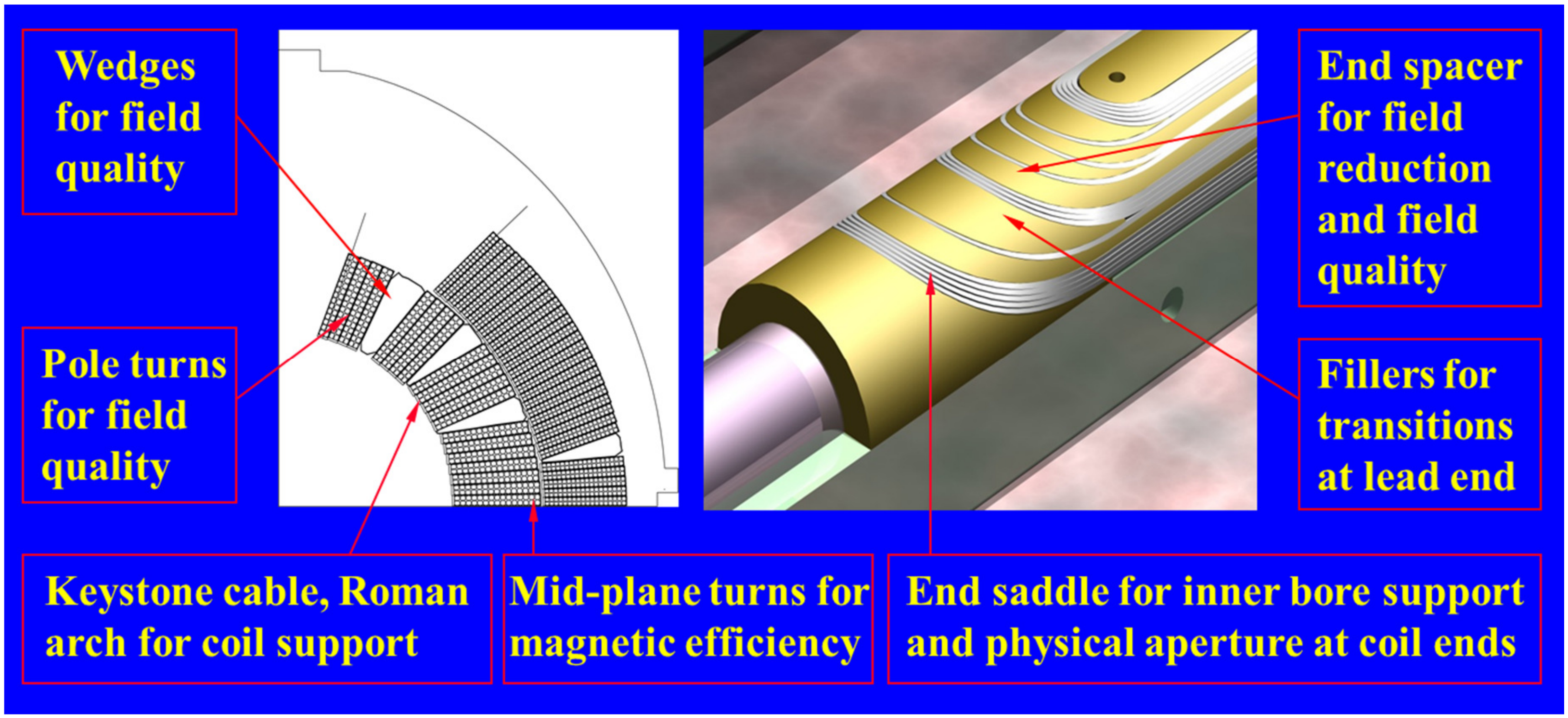




- **All present designs for both eRHIC and JLEIC IR magnets are based on NbTi**
- **Compact Nb_3Sn quadrupoles are being explored by the EIC R&D program**

Magnet Design and Fabrication: Cosθ Coils

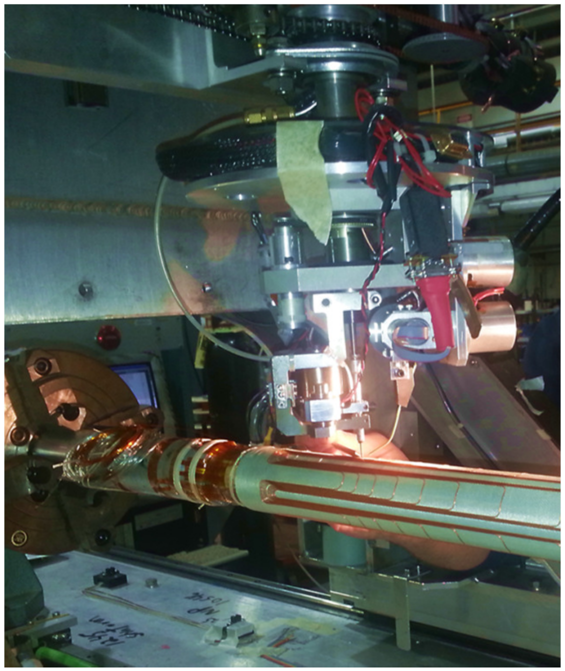
- The *cos*(nθ) coil layout with keystone Rutherford cable has dominated accelerator applications to date due to its efficiency and field quality



- This layout is compatible with both NbTi and Nb_3Sn magnet technology
- However, it requires complex tooling which is specific to each design

Magnet Design and Fabrication: Direct Wind

An automated process providing flexibility in the winding pattern of NbTi coils without a need for dedicated tooling



Main steps in the coil fabrication process:

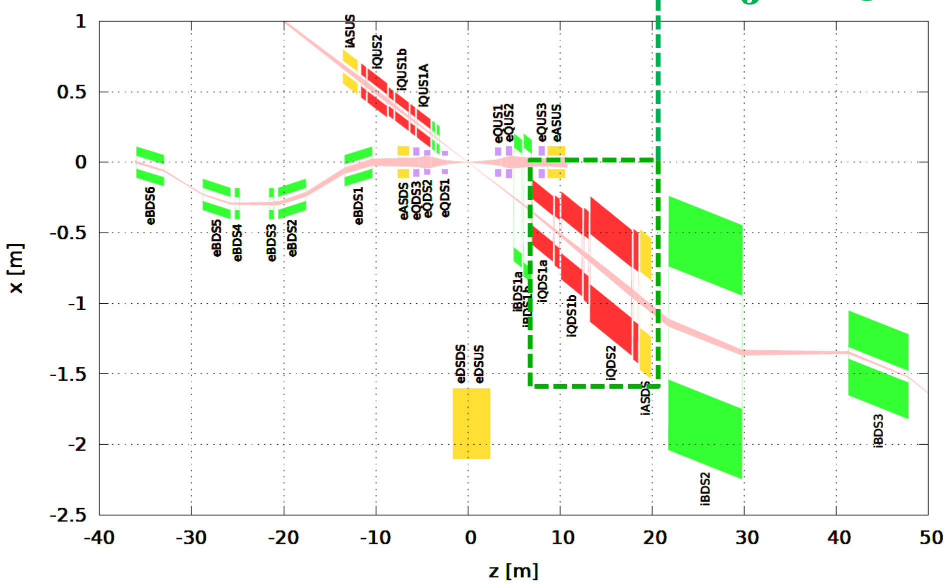
- Support tube is placed on a rotating support and wrapped with epoxy substrate.
- The conductor is epoxy coated and placed in the desired pattern by a winding head mounted on a gantry
- Ultrasonic heating bonds the conductor to the substrate
- After each layer is completed, gaps are filled with spacers (e.g. G10) and epoxy to provide a winding surface for next layer
- A fiberglass wrap is wound under tension to compact the coil layers and provide radial support
- A high temperature cure completes the coil

- Well suited for *complex winding patterns, compactness, active shielding in a moderate field /force range*
- Successfully applied to special magnets for: HERA-II, BEPC-II and ILC IR, J-PARC and BTeV correction coils, Alpha anti-hydrogen trap

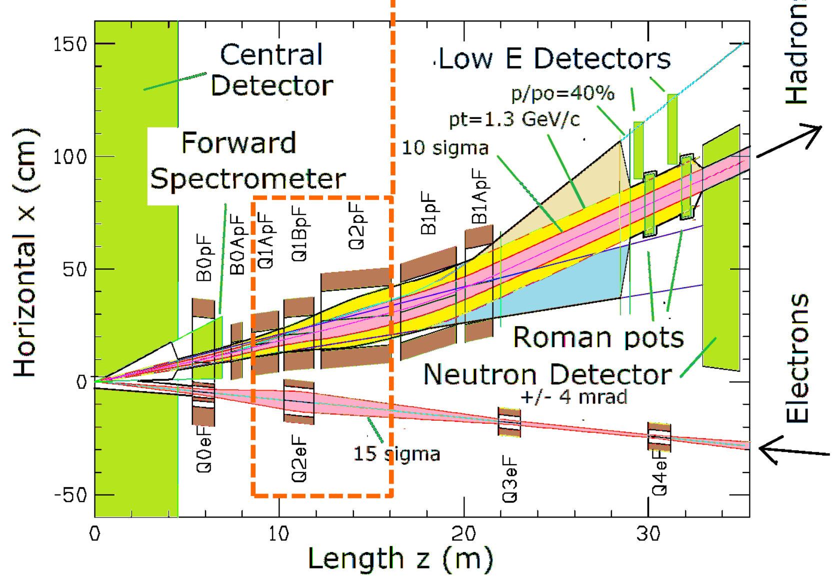
Downstream Hadron Quadrupole Parameters

Parameter	Unit	iQDS1a	iQDS1b	iQDS2	Q1ApF	Q1BpF (Q2eF)	Q2pF
R_{bore}	mm	92	123	177	56	78 (63)	131
G_{normal}	T/m	-37.2	-37.2	26.0	-72.6	-66.2 (8.0)	40.7
$G \times R_{bore}$	T	3.4	4.6	4.6	4.1	5.2 (0.5)	5.3
Z_{IP}	m	8	11	16	9	11	14
$L_{magnetic}$	m	2.25	2.25	4.5	1.46	1.61	3.80

JLEIC



eRHIC



Downstream Hadron Quadrupole Features

Both JLEIC and eRHIC:

- Very large aperture, high field, forces, stored energy
- Cos (2θ) coil layout, strong (collar-based) mechanical structure, high pre-load
- Challenging space constraints, both transverse and longitudinal

JLEIC:

- Aperture range 184-354 mm, pole tip field range 3.4-4.6 T
- Larger transverse envelope available (larger crossing angle): independent hadron/electron magnet cold masses

eRHIC:

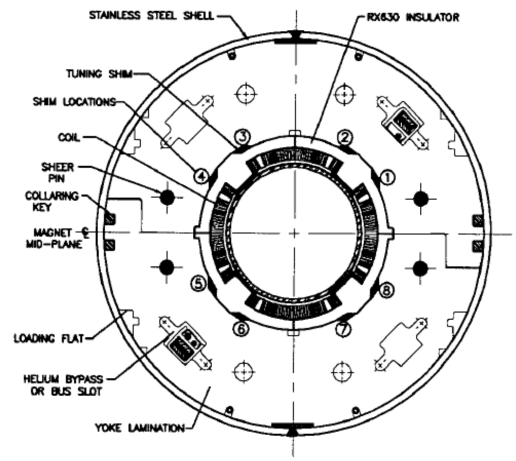
- Aperture range 112-262 mm, pole tip field range 4.1-5.3 T
- Quads are tilted and shifted relative to the beam axis: minimize aperture, maximize iron on the electron beam side avoiding a tapered coil geometry
- No longitudinal gap and bam proximity → Q1BpF/Q2eF in common yoke

Very Large Aperture NbTi Quadrupoles

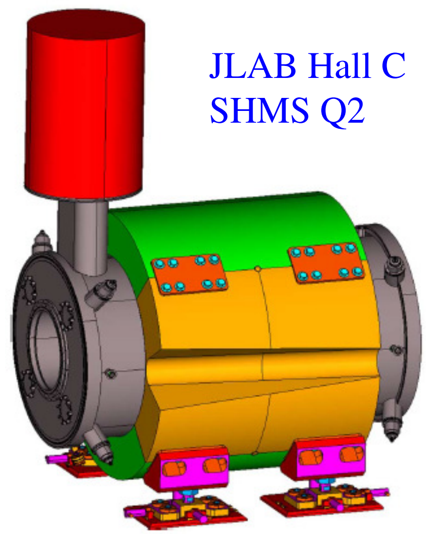
Magnet	Gradient (T/m)	Bore ID (m)	FoD* – G^2R^3 $(T/m)^2m^3$
RHIC IRQ	48	0.13	5.1
eRHIC Q1ApF	72.6	0.112	7.4
JLEIC iQDS1a	37.2	0.184	8.6
CERN ISR	40	0.20	12.8
JLAB Hall C, Q3	7.9	0.6	13.5
AHF Case II	10.3	0.51	14.1
eRHIC Q1BpF	66.2	0.156	16.6
JLEIC iQDS1b	37.2	0.246	20.6
eRHIC Q2pF	40.7	0.262	29.8
JLEIC iQDS2	26	0.354	30
JLAB Hall C, Q2	11.8	0.6	30.1
HIF RPD FFQ	24.2	0.51	77.7

(*) Ref: J. Waynert et al, IEEE Trans. Appl. Supercond. Vol. 11, March 2001, pp. 1522

BNL RHIC IRQ



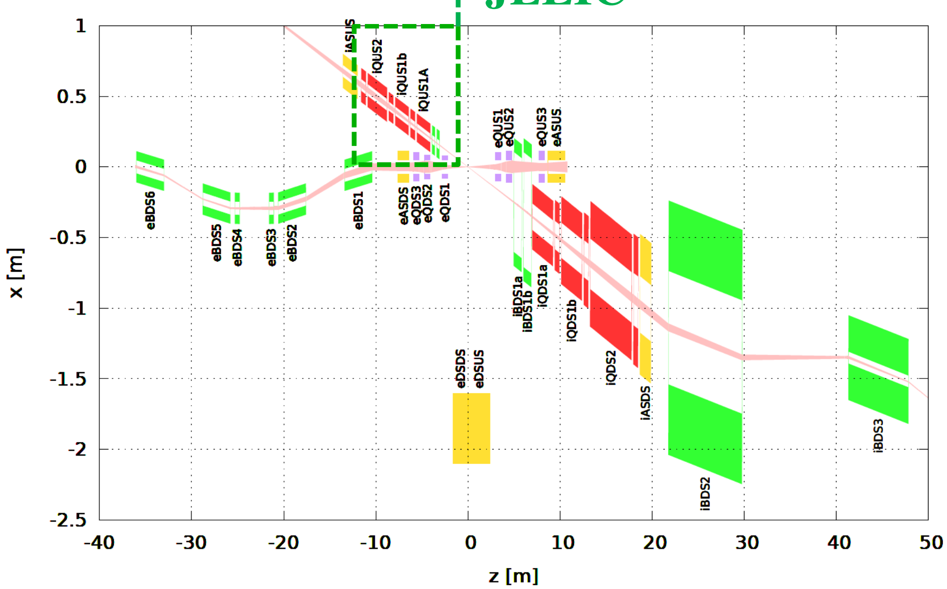
JLAB Hall C SHMS Q2



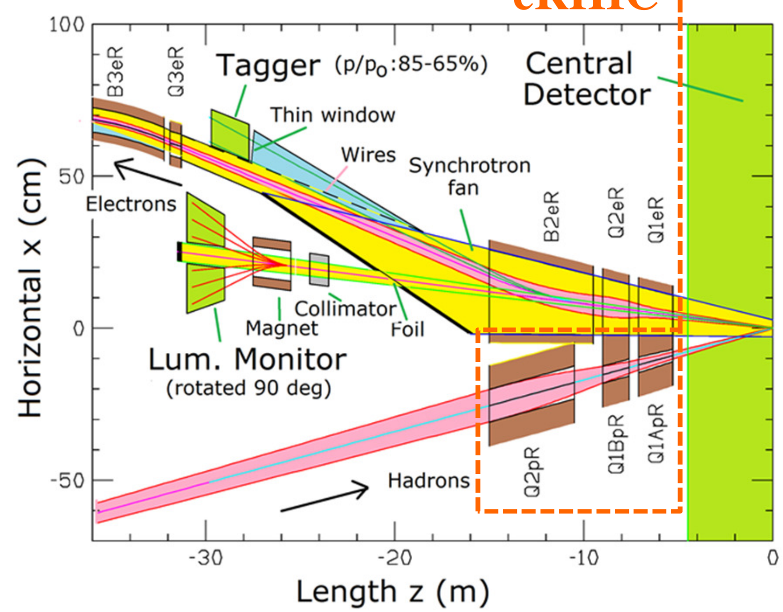
Upstream Hadron Quadrupole Parameters

Parameter	Unit	iQUS1a	iQUS1b	iQUS2	Q1ApR	Q1BpR	Q2pR
R_{bore} *(min/max)*	mm	30	30	40	20 / 26	28	54
G_{normal}	T/m	-97.9	-97.9	94.1	-78.4	-78.4	33.8
$G \times R_{bore}$	T	2.9	2.9	3.76	-2.0	-2.2	1.83
Z_{IP}	m	5	7	10	6	8	13
$L_{magnetic}$	m	1.45	1.45	2.1	1.8	1.4	4.5

JLEIC



eRHIC



Upstream Hadron Quadrupole Features

Both JLEIC and eRHIC:

- Main design parameters (aperture, field, forces etc.) are in the typical range for high energy colliders
  - JLEIC design is more compact with shorter/higher field magnets

JLEIC:

- Cos2θ technology; outer envelope is sufficient for support structure and flux return
- Combination of field and aperture favors a two-layer coil with a ~8 mm wide cable
  - A single layer coil with a ~15 mm cable may also be considered

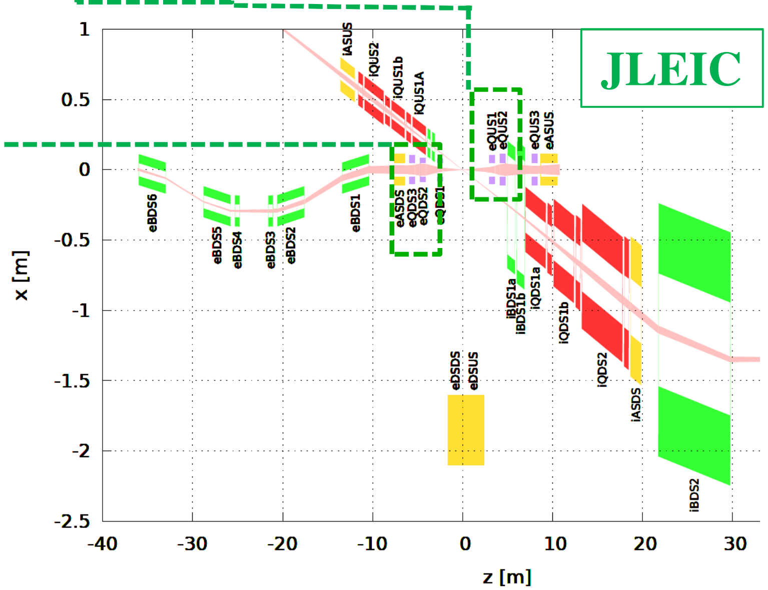
eRHIC:

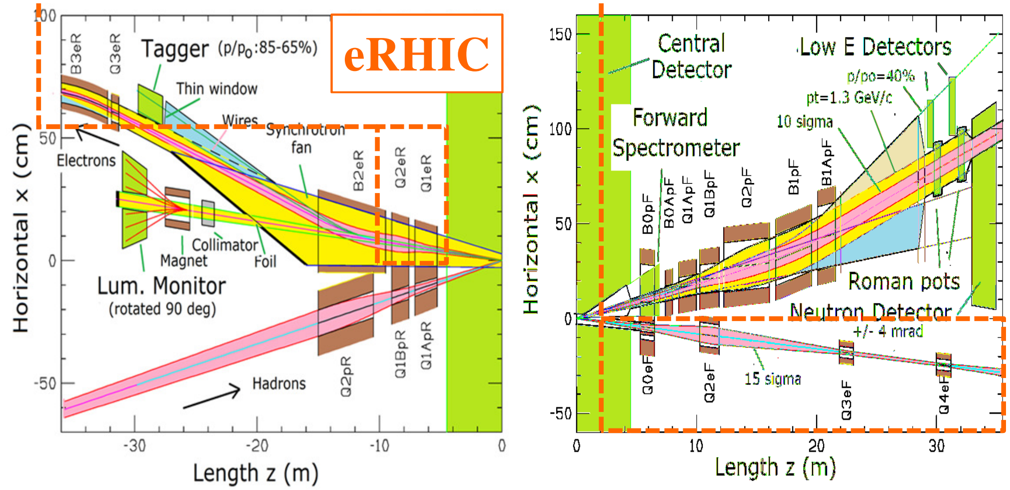
- Close proximity between hadron and electron beam: Q1ApR is tapered and integrated in a common yoke with Q1eR

Electron Quadrupole Parameters

JLEIC	R_{inner}	R_{outer}	L_{mag}	G	B_{pole}
Unit	mm	mm	m	T/m	T
eQDS1	45	8	0.6	-33.7	-1.52
eQDS2	45	8.5	0.6	36.2	1.63
eQDS3	45	10	0.6	-18.7	-0.84
eQUS1	45	10	0.6	-36.9	-1.66
eQUS2	45	11	0.6	33.7	1.52
eQUS3	45	11	0.6	-20.8	0.94

eRHIC	R_{inner} (min/max)	L_{mag}	G	B_{pole}
Unit	mm	m	T/m	T
Q1eR	66 / 79	1.8	-14	-1.1
Q2eR	83 / 94	1.4	14.1	1.3
Q0eF	25 / 28	1.2	-13.5	-0.34
Q2eF	63	1.61	8.0	0.5
Q3eF	30	1.2	-11.6	-0.35
Q4eF	30	1.2	-15.4	-0.46
Q5eF	50	1.2	4.0	0.2





Electron Quadrupole Features

Both JLEIC and eRHIC:

- Basic parameters (aperture, field, forces etc.) are easily achievable
- Main challenge is due to space constraints both on the bore side (synchrotron radiation) and on the outer envelope (proximity of ion beamline)
  - Control field quality and fringe fields

JLEIC:

- Use standard cos2θ technology, but standardize the coil design by using same aperture and length for all magnets (yoke OD is adjusted to available space)

eRHIC:

- Take advantage of direct-wind technology, tailoring each magnet to the specific requirements
  - Some magnets are tapered and use helical coils to control the gradient
  - In some case electron and ion lines are integrated in the same yoke
- Forward magnets further from the IP (Q3,4,5) are normal conducting

Magnet Field Quality: Geometric Errors

Interface with DA studies: field error table including systematic, uncertainty on systematic, and random components

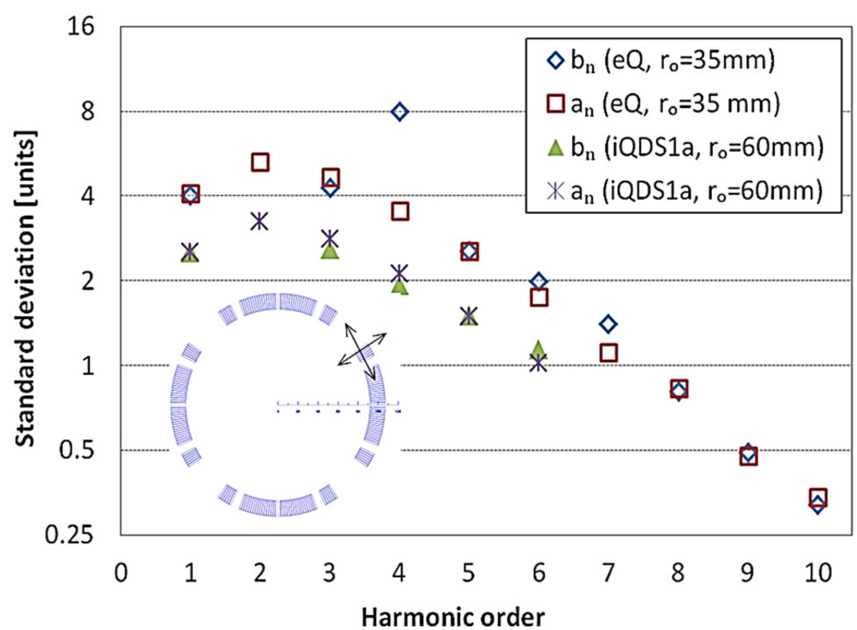
Errors are defined by harmonic expansion: $$B_y + iB_x = B_2 10^{-4} \sum_{n=1}^{\infty} \bar{c}_n \left(\frac{x+iy}{r_0} \right)^{n-1}$$

Harmonic coefficients combine normal and skew components: $$\bar{c}_n = b_n + i\,a_n$$

Random errors:

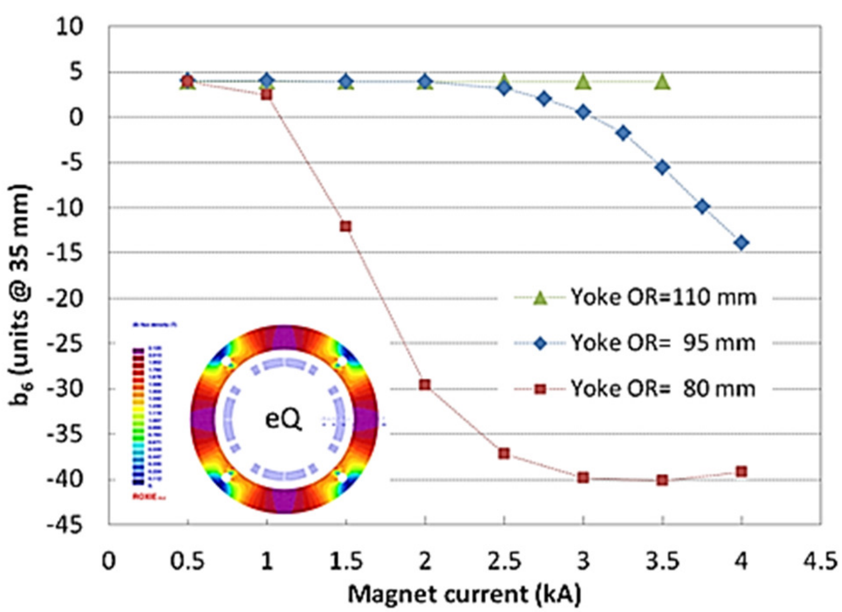
- Effect of fabrication tolerances by Monte Carlo calculation
- Conductor positioning within ±50 µm is usually achieved in cosθ magnet production
- Larger errors may be expected for first (only) units or other design/fabrication methods
- Scaling data from production of similar magnets is also possible

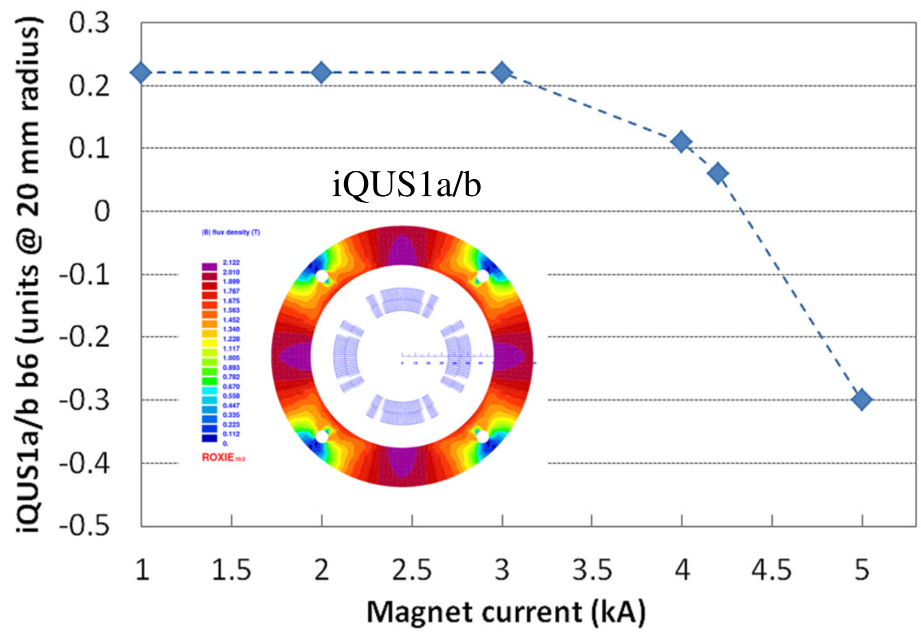
Random errors (1 sigma) for ±100 µm block displacements



Systematic effects: Iron Saturation

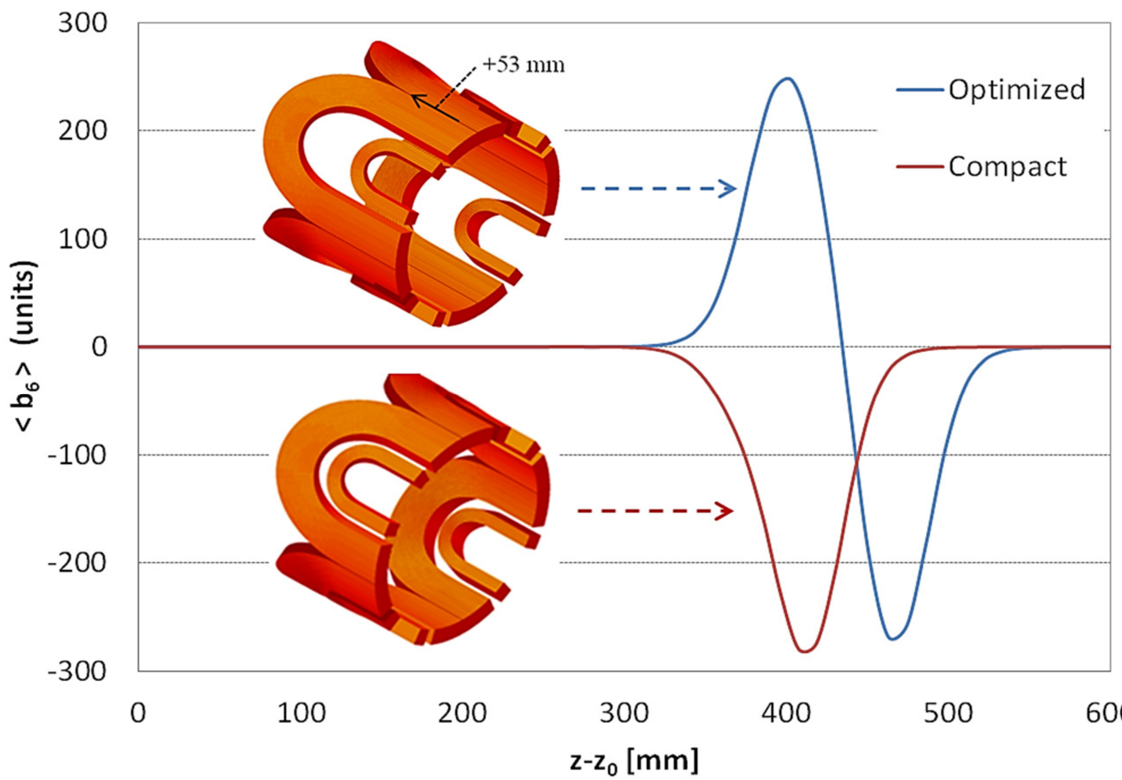
- Operation over a large energy/field range compared to other colliders
- Limited options for yoke optimization due to transverse space constraints
  - Increased distance between yoke OD and coil, increased iron thickness, introduction of features (e.g. holes) to make saturation more uniform
- Requires a specific analysis of each individual magnet
- Cross-section can be modified to shift of the entire curve by a fixed value

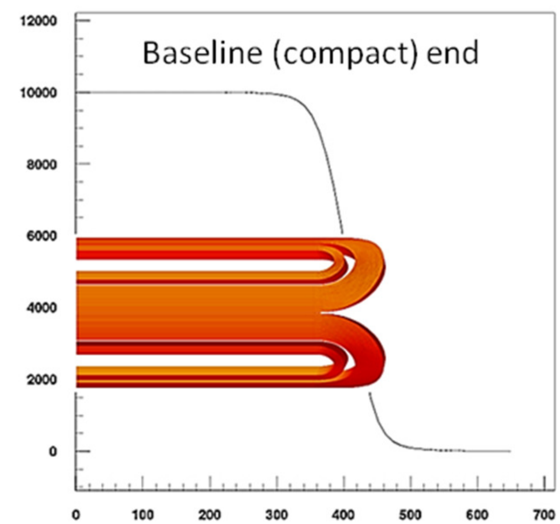


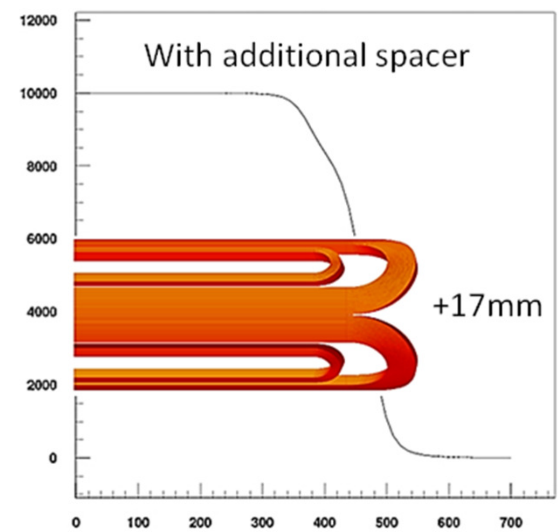


Coil End Optimization: Field Quality

- Integrated harmonics can be corrected with spacers but total magnet length will increase
- For higher order harmonics, need to split blocks
- Feedback from AP will provide guidance

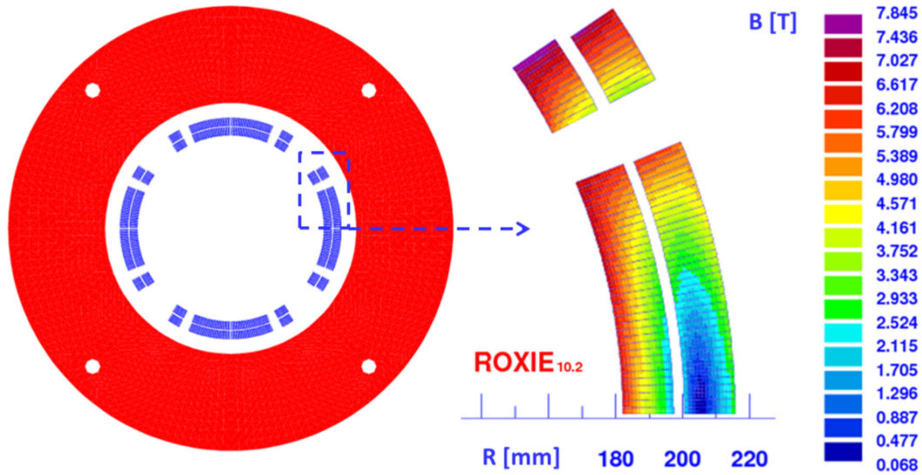


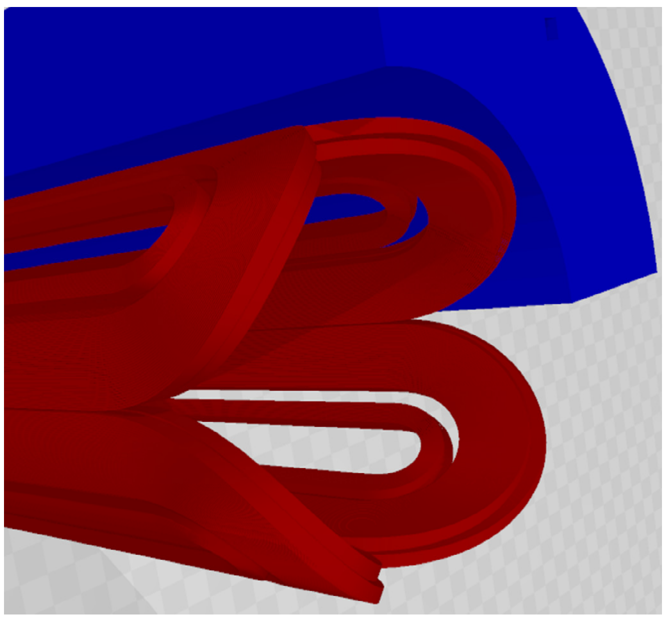


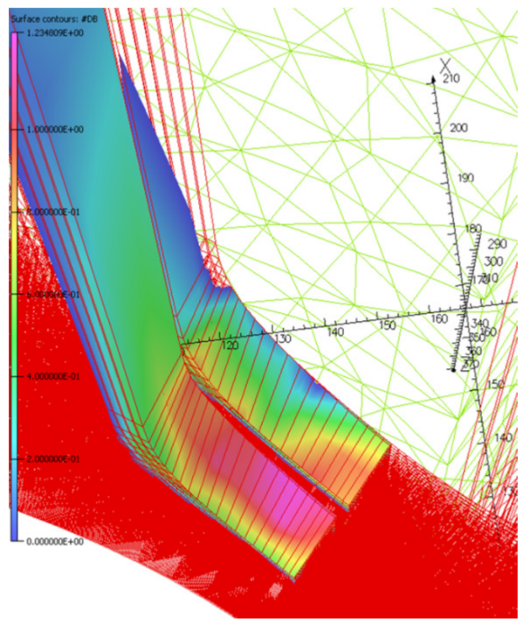


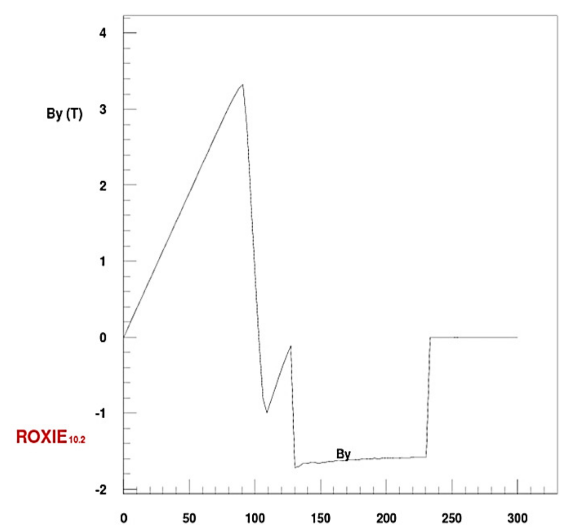
Coil End Optimization: Peak Field

- Coil field may increase by 10-20% in the ends
- Terminating the yoke would increase the fringe field
- Increased block spacing is required to avoid loss of margin



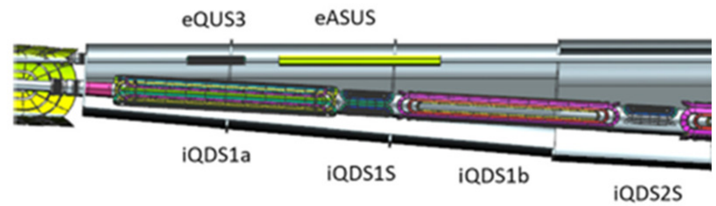




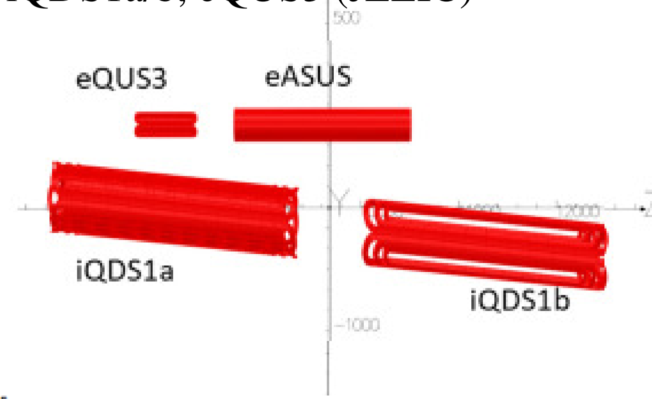


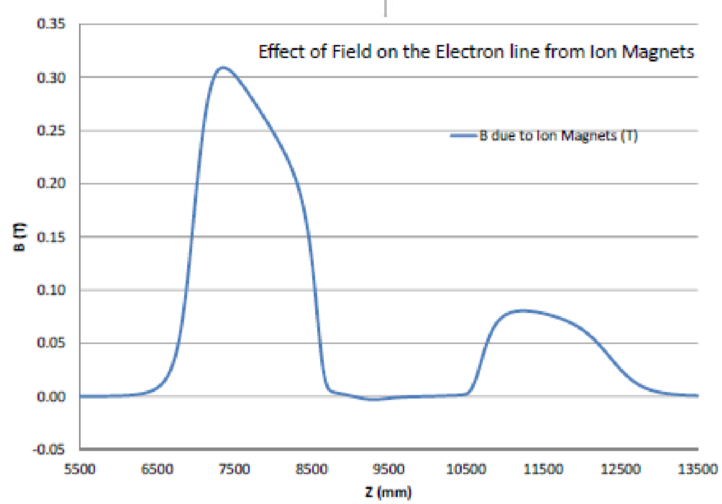
Integrated Electron-Hadron Magnet Analysis

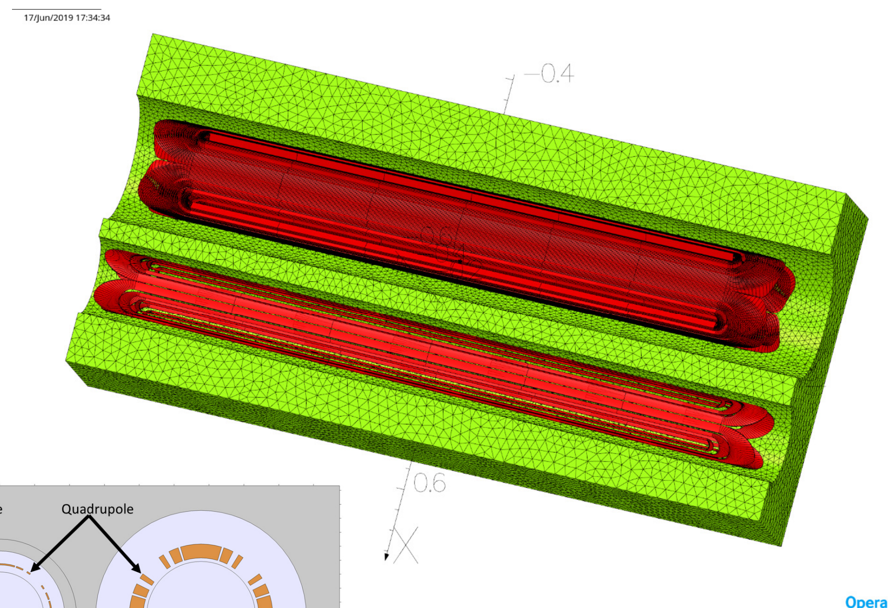
- Models incorporating both beamlines are implemented to study the field errors induced by the adjacent magnets

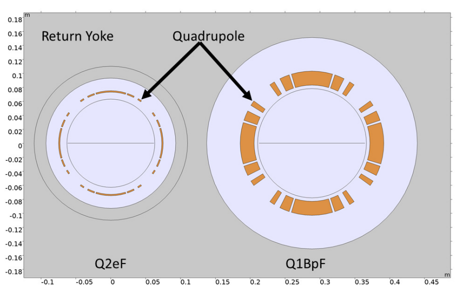


iQDS1a/b, eQUS3 (JLEIC)







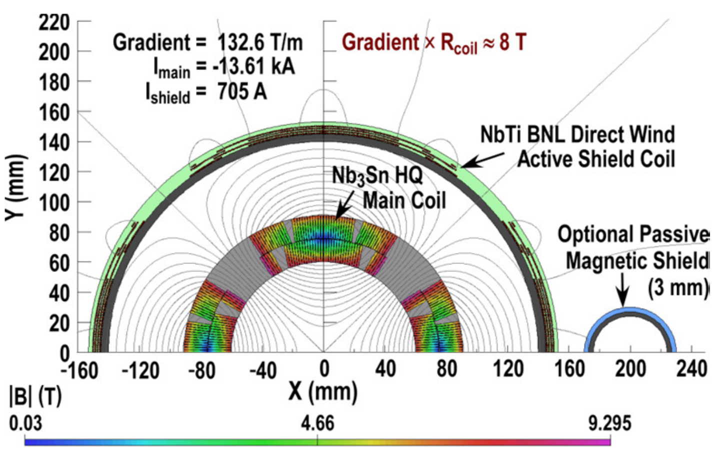


Q1BpF, Q2eF (eRHIC)

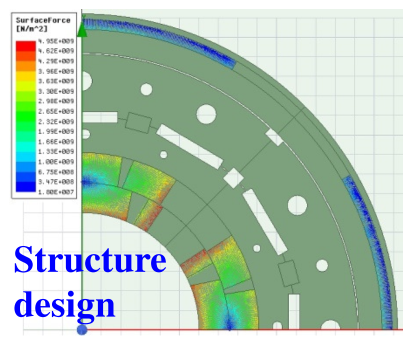
High Gradient Nb_3Sn Quadrupole R&D

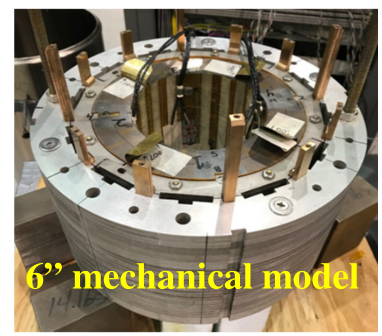
- Nb_3Sn technology is more complex but may offer significant advantages to EIC
  - *Higher gradient $\Rightarrow$ shorter length $\Rightarrow$ smaller aperture $\Rightarrow$ iterate*
- A short model demonstrator is being developed as part of the EIC R&D effort
- Design focus is on compact mechanical structure and reducing the fringe field

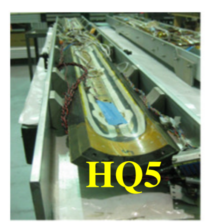
Design Parameters	Unit	Value
Clear aperture	mm	120
Gradient	T/m	133
Peak Field	T	9.3
Current (main coil)	kA	13.6
Current (shield coil)	kA	0.7

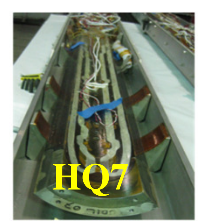


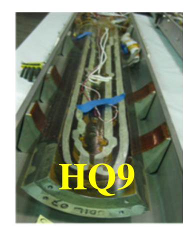
<u>Recent progress</u>: 4 LARP HQ coils selected, QA'd and shipped to BNL; structure design is complete and procurements under way











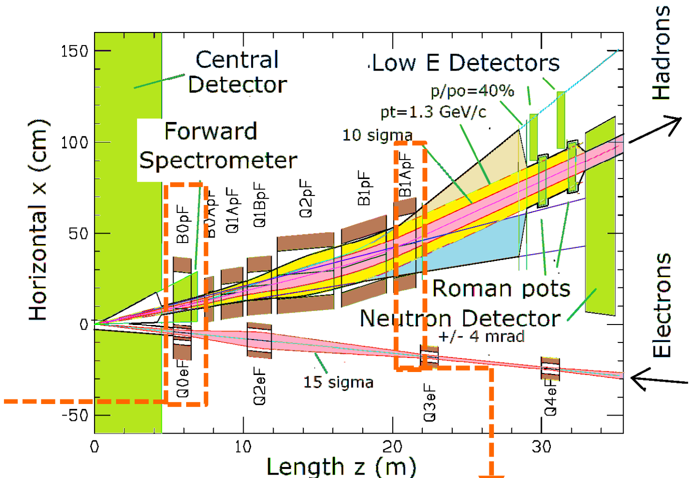
Large Aperture Dipoles

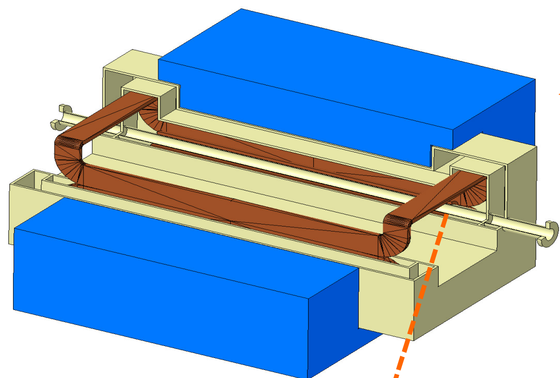
- Design requirements: very large bore and proximity/overlap with electron beam line
- Two examples from eRHIC are shown, but design solutions are also applicable to JLEIC

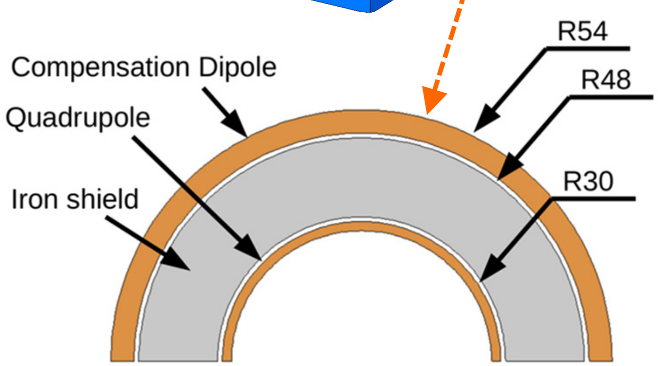
1. B0pF spectrometer: 1.3 T, 200 mm bore

▪ Q0eF is nested in the bore of B0pf

▪ Compensation dipole bucks B0pF. Iron shield cancels residual field and returns Q0eF flux

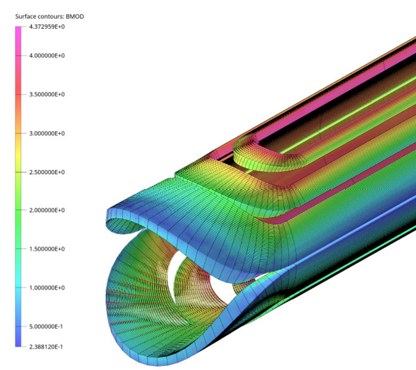


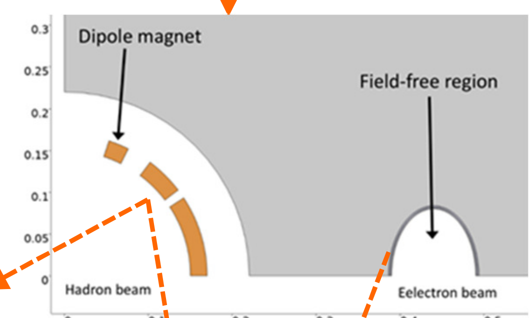


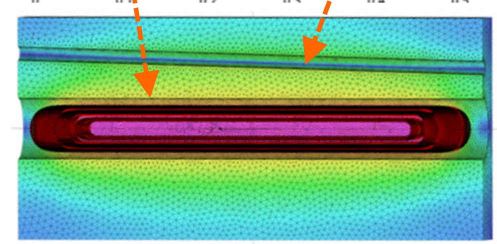


2. B1pF: 3.4 T, 270 mm

▪ Field free channel in yoke for e beam







Summary

- The EIC physics goals place demanding requirements on the Interaction Region layout and magnets
- Significant variety of designs parameters and conditions across the IR
  - Large aperture, high field, proximity of beamlines, detector interface
- A broad range of technologies are being explored to meet these challenges
  - Advanced configurations to fit into the available space and reduce coupling
  - Coil fabrication: combination of traditional approaches, recent advances from HEP colliders and special techniques for flexibility of conductor placement
- Several examples which are representative of the main design challenges and proposed solutions were presented
  - Individual designs were developed for either eRHIC or JLEIC, but they are generally applicable to both colliders
- Current designs are based on NbTi to minimize development time, cost and risk
- A Nb_3Sn quadrupole is under development to address specific EIC and could open the way to alternative layouts with improved performance